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EVALUATION OF METHODS FOR ESTIMATING WIND WAVE GROWTH ON NARROW IRREGULAR FETCHES

by

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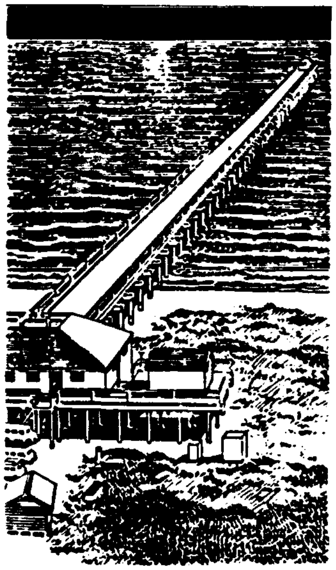

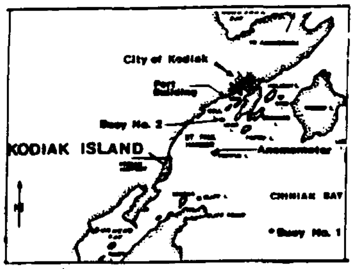

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13. ABSTRACT *(Maximum 200 words)*

The purpose of this study was to compare three different methods for generating wave heights and periods on a narrow irregular fetch with data from a typical Alaskan site. Kodiak, Alaska, was selected because concurrent wind and wave measurements were available for a period of 3 years. Based on wind direction blowing down the narrow fetch to the wave buoy, 79 cases for comparison were chosen. Swell was removed from the buoy data so that only wind waves generated down the narrow fetch were compared. Comparisons were made against the JONSWAP wave growth equations as found in the Shore Protection Manual (1984) or Water Levels and Wave Heights for Coastal Engineering Design (1989), NARFET, a wind-wave generation on restricted fetches analytical model, and STWAVE, a gridded steady-state spectral model.

Results of the study showed that STWAVE matched the buoy wave heights within 0.1 ft based on the mean and that NARFET matched the buoy wave periods within 0.2 sec, based on the mean. This limited study suggests that STWAVE and NARFET, respectively, should be used for determining wave heights and periods for narrow irregular fetches.

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PREFACE

This study was performed in accordance with the requirements of the Coastal Engineering Education Program (CEEP), which is a part of the Corps of Engineers Long-Term Training Program. This one-year program is offered through the Graduate Institute at the US Army Engineer Waterways Experiment Station (WES), by the WES Coastal Engineering Research Center (CERC), and Texas A&M University.

This study was conducted by Mr. Kenneth J. Eisses of the Hydraulics and Hydrology Branch (CENPA-EN-H), US Army Engineer District, Alaska, in partial fulfillment of the requirements for the Master of Engineering degree in Ocean Engineering from Texas A&M University. Work was performed at Texas A&M University, College Station, TX, and at CERC.

Work performed at CERC was under the general administrative supervision of Dr. James R. Houston, Director, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Director, CERC. Mr. Jack E. Davis, Dr. Robert E. Jensen, and Ms. Robin D. Reinhard, all of CERC, greatly assisted in the operation and understanding of STWAVE. Ms. Jane M. Smith, CERC, was also very helpful, especially in analyzing the NARFET results.

Work was performed under the supervision of Dr. Edward F. Thompson, visiting Associate Professor at Texas A&M University and Research Engineer at CERC, Dr. Robert E. Randall, Associate Professor at Texas A&M University, and Distinguished Professor Robert O. Reid of Texas A&M University.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
fathoms	1.8288	metres
feet	0.3048	metres
inches	2.54	centimetres
miles (US nautical)	1.852	kilometres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

EVALUATION OF METHODS FOR ESTIMATING WIND WAVE GROWTH ON NARROW IRREGULAR FETCHES

PART I: INTRODUCTION

Need

Fetch is the distance over water along which the wind can cause wave growth. Wave generation in the open ocean as well as most analytical wave forecasting techniques generally assume fetch width is the same order of magnitude as fetch length. This approach can lead to over-estimates of wave height for a fetch that is narrower than its length or under estimates for a fetch direction that is not aligned with the long axis of the narrow fetch. A great many of the harbor sites in Alaska are quite complicated in terms of determining the design wave. The great majority of these sites have what can only be classified as narrow irregular fetches. The fetch is generally contorted by land boundaries, islands, and shoals. Specific guidance does not currently exist for treatment of narrow irregular fetches. However several promising new models have become available along with traditional fetch limited wave forecasting techniques. An evaluation of these wave forecasting model results for an Alaskan type narrow irregular fetch is needed. Past designs involving narrow irregular fetches in Alaska have had a lot of conservatism built into the design because of uncertainties related to the use of existing wave growth models.

Objectives

The objectives of this study are to compare three different wave forecasting models available for narrow irregular fetch conditions to detailed directional wind data and non-directional wave data. Detailed wind and wave data sets from a narrow irregular fetch environment at Kodiak, Alaska, are used to evaluate the following wave forecasting models:

1.) JONSWAP: wave growth equations, Water Levels and Wave Heights for Coastal Engineering Design (1989).

2.) NARFET: an analytical model for wind-wave generation on restricted fetches, Smith (1991).

3.) STWAVE: a gridded steady state spectral model, Resio (1990).

The results of this study are a comparison of the existing methods using an independent data set and recommendations on how to handle similar narrow irregular fetch wave growth conditions, particularly in Alaska.

Site Description

Kodiak Island is located in the western Gulf of Alaska. Womens Bay and St. Paul Harbor, which lie within the narrow irregular fetch area under study, are near the city of Kodiak on the northeastern shore of Kodiak Island (Figure 1). Kodiak Island is comprised of mostly mountainous terrain with peaks rising to more than 4,000 ft.* The shoreline is

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

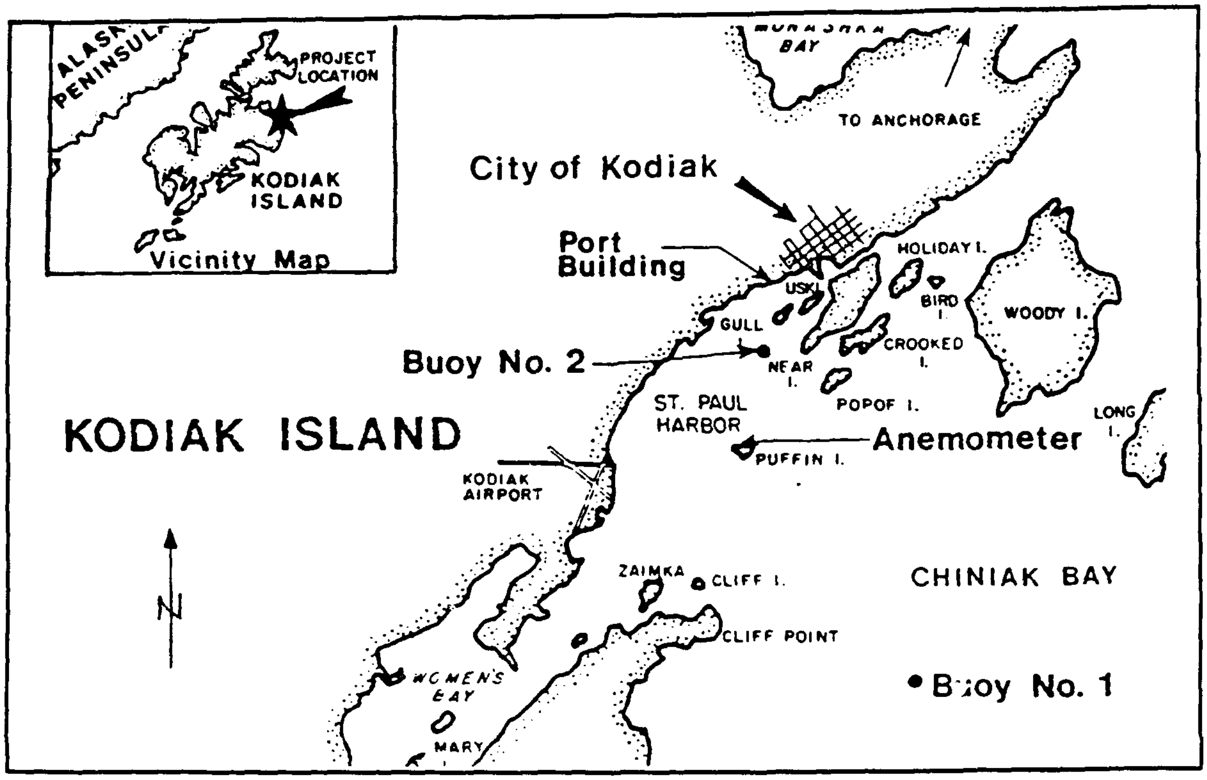


Figure 1. Kodiak Island location and vicinity map

characterized by deep glacial fjords separated by rocky peninsulas and many smaller islands. The Kodiak Island group lies in the path of the Japanese Current, which sweeps northwestward through the Gulf of Alaska. The average annual temperature is 40.7° F.

Tides in the St. Paul and Womens Bay area are characterized by the diurnal inequality common to the Pacific Coast; i.e., one of the two low or high tides

Table 1. Tidal Data, Kodiak, Alaska

Mean Higher High Water	8.5 ft MLLW
Mean High Water	7.6 ft MLLW
Mean Tide Level	4.3 ft MLLW
Mean Low Water	1.0 ft MLLW
Mean Lower Low Water	0.0 ft MLLW

exceeds the other by several feet. Tidal data are shown in Table 1.

The narrow irregular fetch used in this study lies within Womens Bay and St. Paul Harbor. Womens Bay is approximately 4 miles long by 1/2 mile wide. Several spits and islands adorn it's shoreline. Womens Bay opens into St. Paul harbor. The distance from the entrance of Womens Bay to the wave buoy location in St. Paul Harbor is approximately 2 miles and the perpendicular width to this length is 1 mile. St. Paul Harbor is open to the Gulf of Alaska and ocean swell propagates in over an extensive reef system and around numerous islands. Water depths in Womens Bay range from 2 to 17 fathoms. A 2-fathom shoal extends partially across the entrance to Womens Bay from the north. Depths in St. Paul Harbor range from 4 to 10 fathoms. Water depths around Puffin Island average 8 to 10 fathoms. A straight line fetch from the back of Womens Bay to the wave buoy has water depths that range from 8 to 14 fathoms before going over a shoal of 2.3 fathoms then increasing gradually from 4 to 8 fathoms at the wave buoy (Figure 2).

Figure 2 Water depths in Womens Bay and St. Paul Harbor

PART II: FIELD DATA

Alaska Coastal Data Collection Program

The Alaska Coastal Data Collection Program (ACDCP) is a cooperative effort of the State of Alaska Department of Transportation and Public Facilities, the US Army Corps of Engineers, Coastal Engineering Research Center (CERC) and the US Army Engineer District, Alaska. The program is designed to facilitate the collection, analysis, and storage of coastal wind and wave data for use in planning, design, construction, and maintenance of coastal facilities in Alaska. A formal agreement established the ACDCP in 1982. Kodiak was instrumented in September 1981 in conjunction with a port planning study undertaken by the Alaska District and was later incorporated into the ACDCP.

Kodiak was selected for this study because it has an irregular narrow fetch and 3 years of concurrent wind and wave data. There is probably no other similar site with this extensive set of wind and wave data. The fetch is very irregular and very narrow in most places while wider in others. There are islands, shoals and partially blocked wind sectors. Although this is not an ideal narrow fetch it is representative of a typical design site.

The data collection system at Kodiak was comprised of two Datawell Waverider accelerometer buoys which gave nondirectional wave data and a directional Weathermeasure Skyvane anemometer for wind data. Data sampling occurred from October 1981 to September 1984.

Wind Data

The wind station was located on Puffin Island (Figure 1) approximately 2 miles south of the inner buoy. The wind station included a directional wind vane propeller anemometer and a data acquisition unit. The acquisition unit converted analog wind speed and direction measurements into a digital signal that was transferred to the master station by RF telemetry link. Wind speed and direction were sampled once every second by the data acquisition unit. The wind station microprocessor assembled 10 consecutive measurements and calculated a 10-sec average wind speed and direction. These values were transmitted to the master station for further processing. At the end of each hour, 360 of the 10-sec samples were analyzed by microprocessor to determine the following parameters: average wind speed, maximum 10-sec wind speed, average wind direction, and standard deviations of both wind speed and direction. Wind direction is the direction from which the wind is blowing referenced to true north.

Wind events for this study were chosen according to direction and minimum speed criteria. The longest fetch possible between Womens Bay and the wave buoy has a length of 6.2 miles and an azimuth of 220 deg. Fetch direction limits were chosen as 193 and 250 deg. These limits keep the wind wave generation area within Womens Bay and St. Paul Harbor. Puffin Island is 2 miles south of the buoy and blocks wind sectors from 193 to 197 deg. A wind speed threshold value of 8.5 mph was used. This ensured waves that were large enough for the buoy to measure. The anemometer was mounted on top of a 20-ft tower. The base of the tower was at an approximate elevation of 75 ft; therefore, total elevation for the wind sensor was 95.5 ft.

Wind direction versus the number of events for Puffin

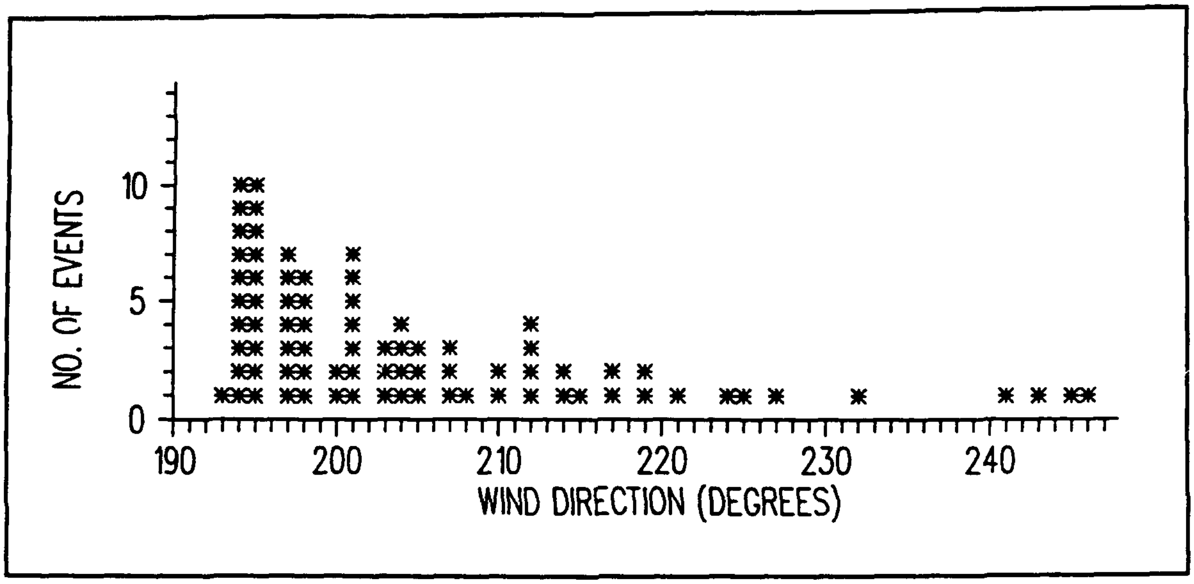


Figure 3. Wind direction versus number of events, Puffin Island

Island was plotted in Figure 3. The objectives of this comparison were to see if the winds preferred the long Womens Bay fetch, i.e. were they channeled by topography and to see if the anemometer orientation was off in any obvious way. The conclusions are the winds are not particular to any one direction and there is not enough information to tell about the anemometer orientation.

In addition, a National Weather Service (NWS) anemometer was located at the Coast Guard Station within Womens Bay. The Coast Guard Station is located on the peninsula protruding into Womens Bay from the north (Figure 1). The anemometer, located in the narrowest part of the fetch, was approximately 100 yd from the shoreline at an elevation of 33 ft and took 5-min average speeds and directions every hour. The NWS anemometer provided data from 1945 through 1982. After the Puffin Island winds were reduced to 33-ft levels, a comparison was made between the 5-min average wind speeds from Womens Bay and the 1-hr average wind speeds from Puffin Island for the 1982 events chosen for this study (Table 2).

Table 2. Puffin Island and Womens Bay Winds

Date	Time	PUFFIN ISLAND Windspeed (mph)	PUFFIN ISLAND Direction (°)	WOMENS BAY Windspeed (mph)	WOMENS BAY Direction (°)
8 Nov 82	0900	7.3	195	9.2	190
10 Nov 82	2100	13.7	194	16.1	190
11 Nov 82	0000	16.4	194	8.0	310
11 Nov 82	0300	20.9	200	8.0	270
12 Nov 82	2100	12.8	198	11.5	190
13 Nov 82	0000	10.9	194	16.1	160
13 Nov 82	0300	15.5	204	11.5	200
13 Nov 82	0600	18.2	195	6.9	200
13 Nov 82	1200	10.0	217	6.9	220
13 Nov 82	1500	10.0	210	10.3	210
8 Dec 82	1200	9.1	197	13.8	220
8 Dec 82	1500	15.5	195	11.5	250
8 Dec 82	1800	9.1	232	5.7	190
27 Dec 82	2100	21.9	198	11.5	160
28 Dec 82	0300	16.4	200	3.4	100
28 Dec 82	1800	8.2	201	25.3	120
29 Dec 82	0900	18.2	195	13.8	180
29 Dec 82	1500	20.0	195	11.5	190
29 Dec 82	1800	19.1	198	9.2	210
29 Dec 82	2100	18.2	201	5.7	280

The 5-min average wind speed does not appear to capture the 1-hr average wind speed and generally is lower than the 1-hr average wind speed. This is possibly due to the gusty nature of the site. The importance of Table 2 is given in the two shaded columns which show the direction of the wind at Puffin Island is very similar to the direction at Womens Bay for most cases and therefore is indicative of the winds over the fetch. The NWS anemometer at Womens Bay only recorded in 10-deg increments. In almost every case the Womens Bay reading at the same time or just before or after was within 10 deg of the Puffin Island reading.

Wave Data

Two Datawell Waverider accelerometer buoys which give nondirectional wave height and period were placed in St. Paul Harbor and Chiniak Bay. Buoy 1, referred to as the outer buoy, was placed in Chiniak Bay at latitude 57°43'10", longitude 152°23'05". Water depth at Buoy 1 was 253 ft. Buoy 2, referred to as the inner buoy, was placed inside St. Paul Harbor at latitude 57°45'55", longitude 152°25'50", and in a water depth of 53 ft.

Data sampling occurred from October 1981 to September 1984. Sea surface elevation samples were collected for 20 min every 3 hr at a rate of 2 Hz, such that a minimum of 2,048 data samples were obtained. The outer buoy was sampled for the first 20 min of the hour and the inner buoy was sampled the second 20 min of the hour. Each record was first edited to remove bad data points, jumps, or spikes caused by data transmission errors. Data points that exceed plus or minus 16.4 ft or data spikes that exceed four standard deviations were removed. A record was rejected if five consecutive bad samples were encountered or if more than 50 bad data samples were found in the record.

After data editing, the variance of the water surface elevation was computed. To improve resolution of wave energy into specific frequencies, a cosine bell data window was applied to the record before the spectral analysis. Records were then analyzed by a Fast Fourier Transform procedure in which a portion of total wave energy is assigned to 1024 discrete frequencies. To improve the stability of each wave spectrum, wave energy was summed over 11 adjacent frequency lines to form 46 frequency bands of width 0.01074 Hz in the region of interest, up to 0.5 Hz. The dominant wave period is then identified as the midpoint of the frequency band containing maximum wave energy. The significant wave height is calculated as four times the square root of the variance. Thus it is an energy based wave height, designated H_{mo}. In deep water, H_{mo} approximately equals H_s.

Spectral wave data are presented in Alaska Coastal Data Collection Program Data Report Number 1, 2, and 3 (1983a, 1983b, 1984). A one-line summary for each record is expressed as Energy Spectrum; Percent Energy in Frequency Bands of Width 0.02148 Hz. These tables include the date and time at the beginning of the data sample, the significant wave height, the total energy or variance of the water surface, and the normalized energy spectrum for each record. Because some suppression of detail was needed for efficient publication of wave spectral data, the normalized spectra were published with 22 frequency bands using a high-frequency cutoff of 0.5 Hz.

The inner wave buoy was the only buoy used in this study because it is within the Womens Bay - St. Paul fetch generating area. Because of its location, the inner buoy was measuring long period swell from the Gulf of Alaska, wind waves and shorter period swell from Chiniak Bay, and short period wind waves from Womens Bay and St. Paul Harbor. In order to obtain only the wave height and period corresponding to the Womens Bay - St. Paul fetch at the inner buoy the energy spectrum tables of the individual wave records were used. In all cases the individual wave records contained low frequency energy which did not have a distinct cutoff between short period wind waves and long period swell from the Gulf of Alaska. A somewhat conservative approach was adopted so that the wave height would not be reduced more than it should be. The peak period which results from the fetch limited JONSWAP equations was used as the cutoff for wind waves. The longest fetch radial possible (6.22 miles) in conjunction with different wind speeds was used in this equation. This allows the largest possible wave growth using the most verified wave equation. The lowest wind speed used in this study becomes fetch limited at a 2.8-hr duration. Higher wind speeds will become fetch limited at a duration time less than 2 hr. The resultant wave height after swell has been removed should be either very close to its true value or slightly conservative for this study. Also each event becomes fetch limited at a duration time less than the buoy sampling frequency of 3 hr. Table 3 gives the cutoff frequency as a function of wind speed as determined from the JONSWAP equations.

Table 3. Wind Wave Low-Frequency Cutoffs

Uc (mph)	Tp (s)	f (Hz)
10-11.9	2.20	.454
12-13.9	2.37	.421
14-15.9	2.53	.396
16-17.9	2.67	.375
18-19.9	2.80	.357
20-21.9	2.93	.342
22-23.9	3.04	.329
24-25.9	3.15	.317
26-27.9	3.26	.307
28-29.9	3.36	.298
30-31.9	3.45	.289

The wave height was obtained by summing the energy in the frequency tables from low frequency to the appropriate cutoff frequency as described above and multiplying by the measured buoy wave height (Equation 1). The tables were summed from low frequency 0.033 Hz (30 sec) toward high frequency 0.484 Hz (2 sec) because energy above 0.484 Hz is not contained on the energy frequency tables and really low frequencies, down to 0.011 Hz, were included in the 0.033-Hz band. In cases where the cutoff frequency fell in the middle of an energy band only half of the energy was summed. H_{sw} in Equation 1 corresponds to H_s for comparison purposes.

The period was determined as the inverse of the frequency which had the most energy in it to the right of the cutoff point.

Wind wave heights and periods (swell removed) that were used for comparison with the other wave growth models are given in Appendix A.

$$H_{sw}=\sqrt{\frac{100-\sum_{i=1}^{N_c} P_i}{100}}H_{st} \tag{1}$$

where

H_{sw} = wave height due to wind, ft

H_{st} = total buoy measured wave height, ft

N_c = frequency cutoff band number, Hz

P_i = percent energy in ith frequency band, percent

PART III: METHODS OF ESTIMATING WAVE GROWTH

JONSWAP Growth Curves

The most common and generally accepted method for calculating wave heights in narrow fetch conditions is to use the JONSWAP wave growth equations described in the Shore Protection Manual (SPM 1984). Fetch length is estimated as an average of nine radials at three degree increments (SPM 1984). The Water Level and Wave Heights for Coastal Engineering Design Manual, EM 1110-2-1414, (1989) uses the same procedures but builds the wind stress factor into the JONSWAP wave growth equations rather than treating it as a separate factor. Since it is easier conceptually to relate wave height to wind speed, rather than to a wind stress factor, the JONSWAP growth equations from EM 1110-2-1414 were used.

Wind speeds measured at the 95.5-ft elevation on Puffin Island were converted to the 33-ft level by use of the following equation:

$$U_{33} = \left(\frac{33}{Z}\right)^{1/7} U_Z \qquad (2)$$

where

U_{33} = the wind speed at the 33-ft level

U_Z = wind speed measured at the 95.5-ft level

Z = 95.5 ft

Generally, wind speeds are converted to a 1-hr duration; however, in this case, the wind speeds are 1-hr average wind speeds and no adjustment is necessary.

Puffin Island is an unusual place to measure winds. The measured winds are being observed over land; however, the winds have already traveled between 1.5 and 4 miles over water before getting to the island. Also, the winds are being formed to a great extent over land before reaching Womens Bay. The interface between land and sea used to determine the overland/overwater correction to use is extremely difficult. The following corrections were considered appropriate for this particular site. Wind speeds observed over Puffin Island were corrected to over water wind speeds by increasing the observed wind speed by 10 percent. Recommended guidance for fetches less than 10 miles is to increase over water wind speeds by 20 percent and omit any correction due to air-sea temperature difference (EM 1110-2-1414). Because the air-sea temperature difference can be large at Kodiak, a stability correction was applied to the wind and only half the normal over-water correction was used.

The stability correction was developed using a combination of climatological data, judgement, and accepted engineering guidance. Temperature corrections were developed using the following. Daily air and sea temperatures were not available. Monthly mean air temperatures were available from the Local Climatological Data for Kodiak, Alaska, for the years 1949-1990. Monthly mean sea surface temperatures came from National Data Buoy Center buoy station 46001 located in the Gulf of Alaska from 1972-1990. These sea surface temperatures are consistent with experience since it is known the waters of Cook Inlet warm up to between 50° F and 55° F in the summer months. The sea surface water in and around Kodiak would be expected to follow the same pattern. Some judgement based on site experience and a knowledge of storm patterns was used along with Figure 5-28 of EM 1110-2-1414 in deriving the final correction factor which was used in the wave growth equations (Table 4).

The recommended procedure for determining the fetch

Table 4. Air-Sea Temperature Corrections for Kodiak

Month	Mean Air Temp (°F)	Mean Sea Temp (°F)	Temp Diff. (°F)	Correction
Jan	31.9	40.5	-8.6	1.17
Feb	29.4	39.6	-10.2	1.17
Mar	32.7	39.6	-6.9	1.15
Apr	38.0	40.6	-2.6	1.10
May	43.2	43.2	0.0	1.00
Jun	49.7	47.5	2.2	1.00
Jul	53.7	52.3	1.4	1.00
Aug	54.8	55.2	-0.4	1.00
Sep	49.9	53.2	-3.3	1.10
Oct	41.2	48.4	-7.2	1.15
Nov	34.7	44.6	-9.9	1.15
Dec	29.6	41.9	-12.3	1.17

length consists of constructing nine radials from the point of interest at 3-deg intervals and extending these radials until they first intersect land. The length of each radial was measured and the radials are arithmetically averaged to give a representative fetch. The fetch distance for each degree between 180 deg and 270 deg was measured and then the appropriate nine radials were used to determine the fetch desired. Maps of these fetch determinations, the small Basic program that was written, and the results are shown in Appendix B.

Significant wave height and peak period were estimated from Equations 3 through 6 using the corrected wind speed and fetch calculated as described above. The equations were developed from the Joint North Sea Wave Project and are called the JONSWAP wave growth equations.

The fetch-limited equations are:

$$H_s = 0.0177\,U_c^{1.23} F^{0.5} \tag{3}$$

$$T_p = 0.4686\,U_c^{0.41} F^{0.33} \tag{4}$$

The duration-limited equations are:

$$H_s = 0.009079\,U_c^{1.58} t^{0.714} \tag{5}$$

$$T_p = 0.2416\,U_c^{0.724} t^{0.411} \tag{6}$$

where

H_s = the significant wave height, feet
T_p = the peak period, seconds
U_c = the corrected wind speed, mph
F = the fetch distance, miles
t = the duration, hours

Significant wave height and period were determined using the fetch-limited equations. These results are shown in Appendix A. The minimum durations corresponding to the fetches were also checked and all were found to be between 1.6 and 2.8 hr. A thorough check through the 3 years of data shows that the average 1-hr wind speed can blow at the same speed for 3 hr or more. Additionally, for each chosen record, the preceding wind speed was checked, and in almost all of the cases the wind speed stayed constant or was increasing for the 3-hr interval preceding the chosen record. Therefore, the wave heights and periods were not considered restricted by duration but only by the fetch.

NARFET Model

The NARFET model (Smith 1991) is based on the concept of allowing wave generation in off-wind directions. Using data from the Great Lakes, Donelan (1980) proposed a model for wave generation over fetch lengths in off-wind directions with wind forcing reduced by the cosine of the angle between off-wind and wind directions. This approach allows for a balance between a reduced wind speed $U_c \cos \phi$, where ϕ is the angle between the wind and wave direction, and an increasing fetch distance in the off wind direction. Donelan developed different relationships for wave height and period than those equations derived from the JONSWAP experiments. His approach is based on the premise that the dominant direction for wave generation is that for which the following product is maximized:

$$(\cos \phi)^{0.54} F^{0.23} \tag{7}$$

This product is a function of fetch geometry. Donelan's equations, which gave very good results on the Great Lakes, are:

$$H_s = 0.00366 g^{-0.62} F^{0.38} (U_c \cos \phi)^{1.24} \tag{8}$$

$$f_p = 1.85 g^{0.77} F^{-0.23} (U_c \cos \phi)^{-0.54} \tag{9}$$

where

f_p = peak frequency, Hz (peak frequency is the inverse of peak period)

g = gravitational acceleration, ft/sec^2

F = an averaged straight line fetch in the direction of the waves, miles

This method has been successful in the Great Lakes, but has not been tested for very irregular or narrow fetches. Smith (1991) nondimensionalized and plotted a total of 54 wave data sets from Puget Sound, Washington; Fort Peck Reservoir, Montana; Denison Reservoir, Texas; and Lake Ontario to seek improved expressions for wave height and peak frequency on restricted fetches. The data sets were chosen to have steady wind speed and direction, and sea conditions that were fetch-limited rather than fully developed or duration-limited. Wind speeds were averaged over the duration for each case, adjusted to the 33-ft elevation and adjusted for air-sea temperature difference (SPM 1984). Wave heights were between 0.7 and 6.5 ft and periods ranged from 2.2 to 6.6 sec. Linear regression of the non-dimensionalized data sets resulted in Equations 10 and 11,

$$H_s = 0.0015 g^{-0.5} F^{0.5} (U_c \cos\phi) \tag{10}$$

$$f_p = 2.6 g^{0.72} F^{-0.28} (U_c \cos\phi)^{-0.44} \tag{11}$$

Correlation coefficients between predicted and measured wave parameters in Smith's data set are better for Equations 10 and 11 than for the Donelan model. For simple straight-line fetch situations the results are similar to the JONSWAP growth curves. For narrow irregular fetch conditions in which the wind direction is other than the main fetch, Smith's model does a better job of predicting wave height and period than the simple fetch calculations of the Shore Protection Manual.

In the present study, the NARFET computer code was run for the 79 selected Kodiak cases. Wind speeds input to NARFET were those for the 10-m elevation, and the same air-sea temperature correction as in the JONSWAP equations. Fetch lengths were entered at 3-deg spacings from 181 to 268 deg. NARFET internally interpolates fetch lengths at 1-deg increments and then averages fetch length over 15-deg arcs for computations. Initial predictions with NARFET overestimated measured wave heights by over 50 percent. Upon investigation, it was discovered that the released version of NARFET has a correction for nonconstant coefficient of drag which was not included in the version of the model used to determine Equations 10 and 11. This correction was then removed from the NARFET model used in this study. Complete results from these runs are given in Appendix A.

STWAVE Model

The STWAVE program is a computationally efficient finite-difference numerical model for nearcoast time-independent spectral wave energy propagation and generation simulations. The program was developed by Dr. D. T. Resio of Ocean and Coastal Technology, Inc. (Resio 1990) and was implemented in the Coastal Modeling System (CMS) at CERC by Jack Davis. The efficiency of the program is due to the assumption that only wave energy directed into the computational grid need be considered. The program is time independent, meaning wave conditions at a point do not change relative to the time required for waves to pass across the computational grid. These assumptions limit the model to nearcoast applications in which waves are generally directed into the grid and move quickly across it, generally within 0.5 hr. These assumptions are appropriate for the Kodiak cases being considered.

STWAVE is based on a simplified form of the following spectral balance equation, in which variables are functions of space although not explicitly written as such,

$$\frac{\partial[cc_g E(f,\theta)]}{\partial x} + \frac{\partial[cc_g E(f,\theta)]}{\partial y} = S_{at} + S_{br} \qquad (12)$$

where

E = spectral energy density for the given f, θ

f = frequency of spectral component

θ = propagation direction of spectral component

S_{at} = source term for atmospheric energy input

S_{br} = sink term for surf-zone breaking

The rate of change of a spectral energy component with respect to time for a given location is not used in this model. The terms on the left hand side of Equation 12 represent the advection of a spectral energy component and include refraction and shoaling based on phase speed (c) and group speed (c_g).

The atmospheric energy generation within STWAVE uses the parametric form of the JONSWAP growth rates. For wind generation, STWAVE simulations require wave frequency limits and intervals at the input boundary of the computational grid. STWAVE generates a wave energy spectrum and propagates it from grid point to grid point, starting at the input boundary. The transformation of each spectral component in frequency and direction includes refraction and shoaling effects. Additional energy due to atmospheric input is added at each grid point. When the propagation of the entire spectrum to the new column is complete, it is evaluated for breaking conditions. When a spectrum is considered breaking, the energy levels within the spectrum are limited to levels defined by Davis et al. (1991). The spectra along the new column are then propagated to the next column along with additional energy input. When a land point within the grid is encountered, the total spectral energy for that point is set to zero. Also, the energy levels for spectra on the boundaries of the grid are set to the values of the spectra on the rows or columns adjacent to the boundaries. The input boundary spectrum is applied to all points on the boundary except land points which are assigned zero spectral energy values.

All STWAVE simulations for this study were run on the WES Cray Y-MP computer. A 0.3-in. grid was overlaid on Kodiak chart 16595 because this size grid defined Puffin Island with several grid boxes. This resulted in a 68 by 30 grid. Grid cells were square and when scaled to prototype dimensions each side equalled 500.3 ft. The grid represented all of the Womens Bay shoreline, the northwest shoreline of St. Paul Harbor, 2,000 ft northeast of the wave buoy, and out to the reefs which define St. Paul Harbor. The numerous islands and shoals were included in the grid. The long axis of the grid was aligned with the longest fetch direction to the buoy at 220 deg. Water depths at each grid point were entered in a separate file with 0.0 used to delineate land. Initial water depths used were those at 0.0 ft MLLW directly from the NOAA chart. Later runs were increased by a water depth equal to MHHW, a difference of 8.5 ft, but land/water boundaries remained unchanged. The effect of water depth on wave growth was minimal. Wave heights changed in most cases between 0.03 and 0.13 ft and some periods increased by 0.1 sec. Results from only the 0.0-ft MLLW runs were used in the following sections.

The wave energy spectrum is defined over frequency and direction. Twenty frequency bands were used to discretize the wave energy spectrum in these runs. The frequency bands ran from 0.083 Hz to 1.333 Hz in 0.063-Hz increments. A value of 18 directional bands was used, as recommended in the model, yielding 10-deg angle band widths.

Output from STWAVE was obtained at a grid point which coincided with the buoy position. Since this is a spectral model the wave height is an energy based wave height H_{mo} and the period is based on the frequency band with the highest energy density. Output options in the CMS include plots of the grid, wave height contours, period contours and wave vector directions. Examples of these are shown in Appendix A. The wave height and period for the grid point that coincided with the buoy was obtained from an output file and listed in the data table in Appendix A.

PART IV: RESULTS & COMPARISONS

JONSWAP to Buoy Data

Scatter plots of the 79 cases comparing JONSWAP wave heights and periods to buoy wave heights and periods are shown in Figures 4 and 5. The JONSWAP equations underpredicted wave height in most of the cases and underpredicted wave periods in nearly every case. For cases in which the wind direction was aligned with the long axis of the fetch, predicted wave heights came reasonably close to the buoy wave heights. However, when the wind approached at a significant angle to the axis of the long fetch(approximately 20 deg to 25 deg for this study), the average fetch was severely shortened by between 50 and 100 percent, and wave height was underpredicted. There is nothing definitive that can be said about the periods other than they compare poorly, even the periods along the long fetch cases underpredicting by 0.5 to 0.8 sec.

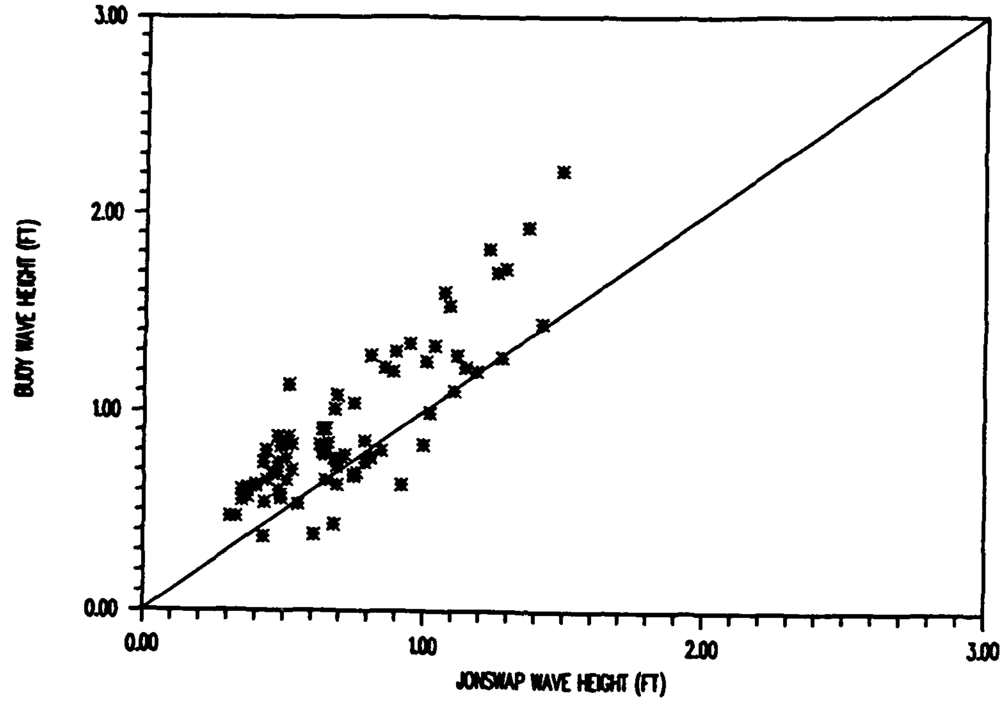


Figure 4. JONSWAP versus buoy wave height

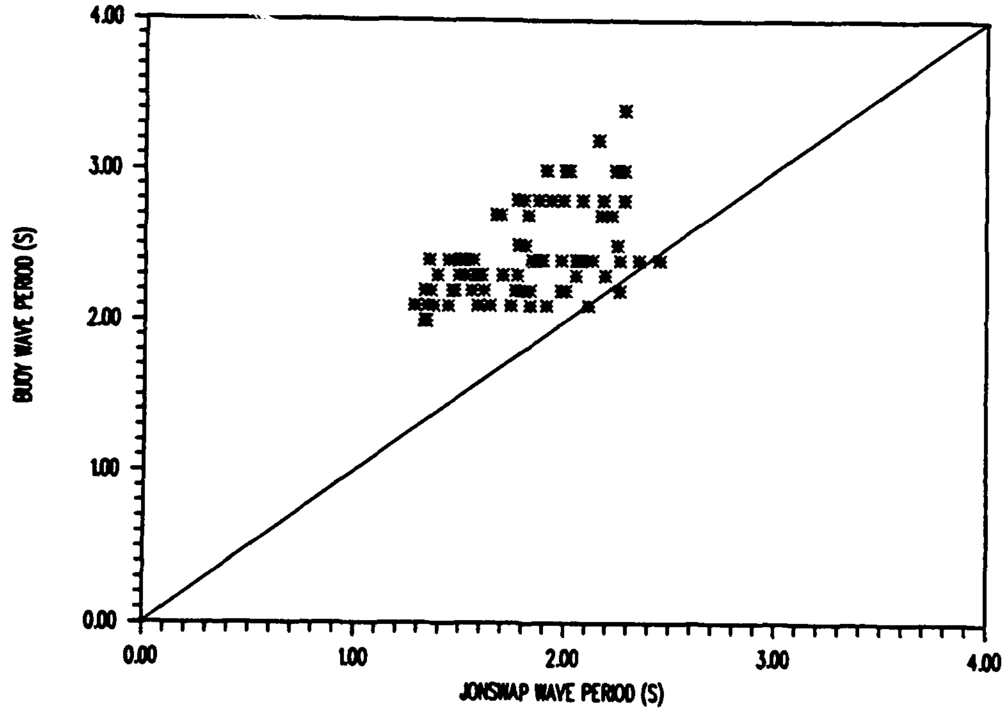
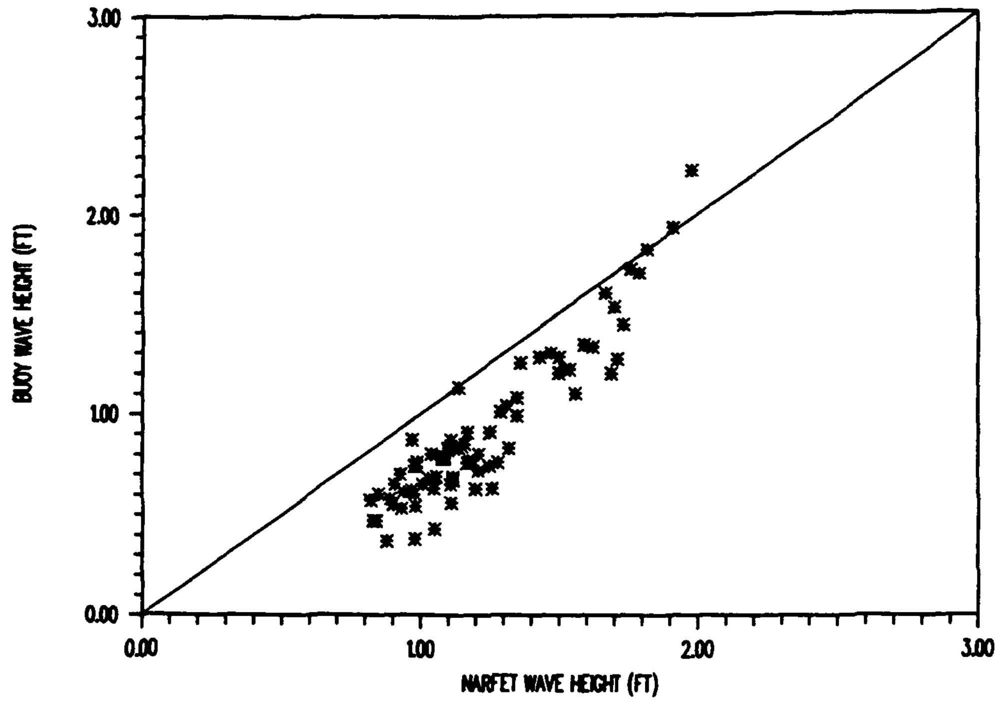


Figure 5. JONSWAP versus buoy wave period

NARFET to Buoy Data

Scatter plots of the 79 cases comparing NARFET wave heights and periods to buoy wave heights and periods are shown in Figure 6. In almost every case, NARFET overpredicts the wave height. The overprediction is about 0.3 ft except for the highest wave conditions which were well-predicted by NARFET. The reason for the overprediction for wave heights less than 1.5 ft is probably due to the over water/over land correction which NARFET uses. This correction to U_c is a factor of 1.3 to 1.4 for low wind speeds and gradually decreases to a factor of 1.0 to 1.1 for higher wind speeds. Smith (1991) did not have low wind speeds like those used in this study.

The wave period plot shows reasonably close agreement between NARFET and the buoy, with NARFET exhibiting a small tendency toward underprediction. Overall, the period comparison is remarkably good, considering the uncertainties in identifying peak period in the high frequency part of the buoy spectra.



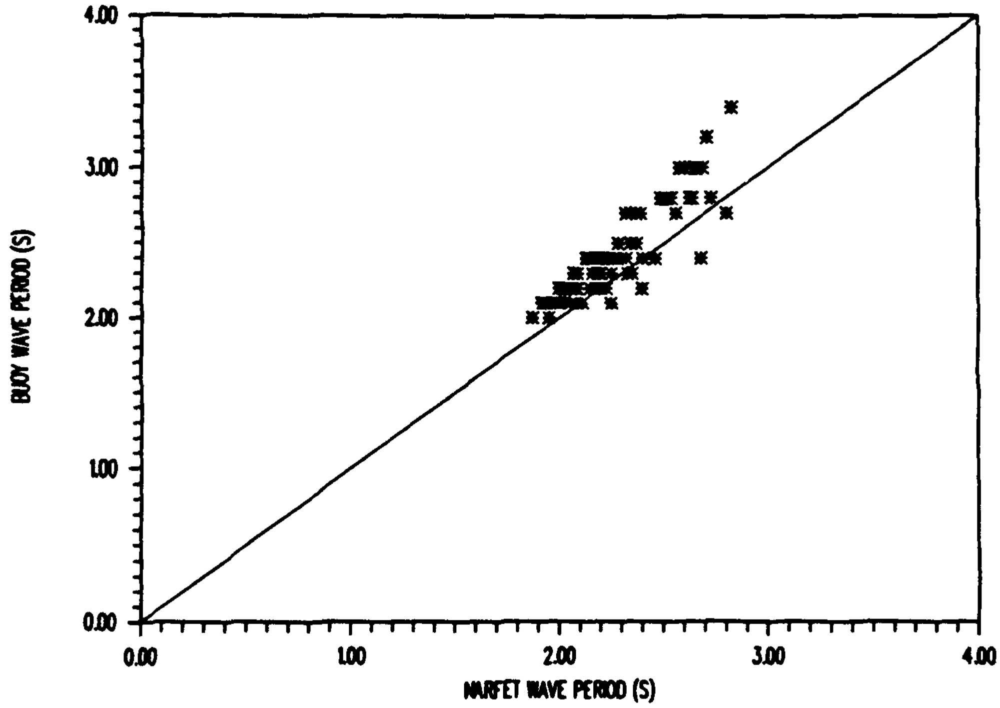


Figure 6. NARFET versus buoy wave data

STWAVE to Buoy Data

Scatter plots of the 79 cases comparing STWAVE wave heights and periods to buoy wave heights and periods are shown in Figure 7. The wave heights from STWAVE and the buoy are quite similar with a small amount of scatter. For the most part STWAVE is slightly overpredicting wave height, which is desirable for design. STWAVE underpredicted wave period in every case, with the difference being an average of about 0.5 sec.

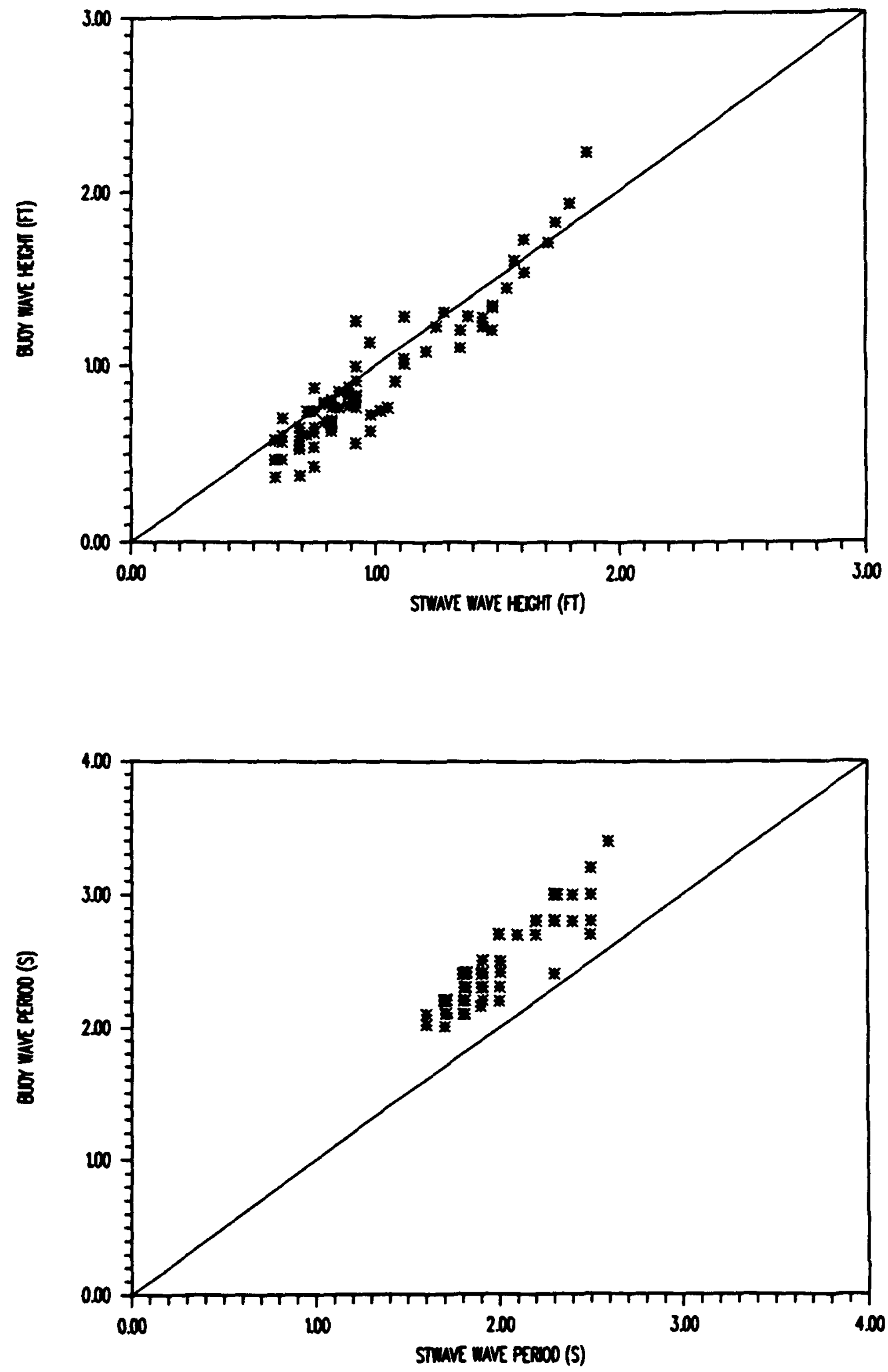


Figure 7. STWAVE versus buoy data

Intercomparison of Methods

A statistical analysis was performed on predictions by the different methods a: ' data from the wave buoy. Calculated parameters were the mean, standard deviation, slope of a one parameter regression line constrained to pass through the origin, and corresponding correlation, r. Statistical parameters for significant wave heights are shown in Table 5. The slope of the regression line is the most telling. It, as well as the mean, shows STWAVE predictions tended to be within 10 percent of the buoy wave heights. The JONSWAP and NARFET means and slopes indicate differences of about 20 - 35 percent relative to the buoy. The correlation was highest for STWAVE, but also high for NARFET. Overall, STWAVE predicted significant wave height better than the other methods.

Table 5. Wave Height Statistics

	Mean	Std Dev	Slope	r
JONSWAP	0.728	0.292	1.24	.846
NARFET	1.222	0.287	0.74	.930
STWAVE	0.991	0.328	0.91	.936
BUOY	0.904	0.378	1.00	----

The buoy wave height data showed a greater standard deviation than any of the prediction methods. This is probably due to non local energy in the wave record spectrum. The standard deviation for the buoy is not significantly greater than the other prediction methods.

A statistical analysis was also performed on the wave periods (Table 6). The slope of the zero intercept regression line shows that NARFET matched the buoy data the best. Both the slope and mean period show that NARFET predictions tended to be within 10 percent of the buoy periods. Differences for

Table 6. Wave Period Statistics

	Mean	Std Dev	Slope	r
JONSWAP	1.810	0.299	1.34	.528
NARFET	2.273	0.233	1.07	.882
STWAVE	1.959	0.248	1.24	.900
BUOY	2.431	0.299	1.00	----

periods from the other methods were much greater, on the order of 20 - 35 percent. The NARFET predictions correlate well (0.88) with the buoy data. The STWAVE predictions correlate even better (0.90), indicating some adjustments to the STWAVE model may be possible to achieve better period predictions. Overall NARFET predicted periods better than the other methods.

Cases with fairly constant wind speed and direction over more than one 3-hr interval were chosen for special consideration. These cases are shown in Table 7. Consecutively numbered sets are 3 hr apart and the dashed lines separate events. This clearly shows that each event is fetch limited because the wave heights have not increased in height over several constant events. These cases are somewhat representative of the entire sample and some general qualitative observations are: For wave height, NARFET overpredicts, JONSWAP is close only if the long fetch is used, and STWAVE matches very close. Only NARFET comes close for predicting periods. The JONSWAP results are a little misleading because these longer duration storms tended to blow from directions greater than 200 deg, at which point JONSWAP results come from the longest fetch and match the data better.

Table 7. Cases with Constant Wind Speed and Direction

		JONSWAP		NARFET		STWAVE		BUOY	
Set	θ	H_s	T_p	H_s	T_p	H_{mo}	T_p	H_s	T_p
11	217	0.81	2.11	1.17	2.25	0.85	1.80	0.76	2.10
12	210	0.79	2.07	1.16	2.24	0.85	1.80	0.85	2.40
20	195	1.23	2.08	1.82	2.73	1.74	2.50	1.82	2.80
21	198	1.26	2.16	1.79	2.71	1.71	2.50	1.70	3.20
22	201	1.29	2.24	1.76	2.69	1.61	2.50	1.72	3.00
23	210	0.72	2.00	1.09	2.19	0.79	1.80	0.78	2.20
24	215	0.92	2.19	1.26	2.33	0.98	1.90	0.63	2.30
25	219	0.81	2.10	1.19	2.26	0.89	1.80	0.77	2.40
44	198	0.71	1.78	1.28	2.34	1.05	2.00	0.76	2.50
45	193	0.49	1.49	1.10	2.19	0.92	1.90	0.82	2.30
46	195	0.65	1.69	1.25	2.32	1.08	2.00	0.91	2.70
67	214	1.12	2.35	1.43	2.46	1.12	2.00	1.28	2.40
68	204	0.68	1.85	1.18	2.26	0.92	1.90	0.76	2.40
69	219	1.01	2.26	1.36	2.40	0.92	2.00	1.25	2.40

PART V: CONCLUSIONS

The conclusions given in this section are based on evaluation of 79 cases at Kodiak, Alaska. The conclusions should be considered preliminary until they can be supported by data from other similar sites. The biggest concerns in the Kodiak data set used are the wind estimation, swell removal, and the fact that there weren't more strong storm events. Conclusions are as follows:

1) For design, it is recommended to run both NARFET and STWAVE. If the wave heights are similar from both models, then the wave height is consistent with both empirically and theoretically derived models. If the wave heights are significantly different, then the STWAVE wave height should be favored. The wave period from NARFET should be used in preference to the wave period from STWAVE.

2) If the JONSWAP growth curves are the only method available for use in a narrow irregular fetch environment, then the average fetch distance should coincide with the longest fetch possible without regard for wind direction, assuming the wind is generating a wave down the fetch.

3) The correction for non-constant coefficient of drag should not be used in the present version of NARFET.

4) The formulation in STWAVE for period growth on narrow irregular fetches should be re-examined and, if possible, improved.

5) The over-land / over-water correction for low wind speeds in NARFET should be re-examined and, if possible, improved.

6) The corrections that are used to derive the corrected wind speed for wave prediction need to be expanded for different types of sites.

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APPENDIX A: NUMERICAL RESULTS AND COMPUTATIONS

Data Set	Date	Time	One Hour Average Wind speed (mph)	One Hour Average Wind direction (°)	Corrected Wind speed (mph)	Fetch, 9-radials-3° increments (miles)
47	23 Apr 83	0900	19.09	194	19.85	1.36
48	23 Apr 83	1200	9.53	194	9.91	1.36
49	24 Apr 83	0000	11.67	205	12.13	2.88
50	24 Apr 83	0600	11.67	197	12.13	1.59
51	28 Apr 83	2000	12.71	212	13.21	4.0
52	28 Apr 83	2300	10.60	194	11.02	1.36
53	2 May 83	0200	9.53	208	9.01	3.50
54	15 May 83	0200	9.53	194	9.01	1.36
55	17 May 83	2000	10.60	214	10.02	4.05
56	21 May 83	0200	9.53	245	9.01	1.97
57	1 Jun 83	0500	14.84	201	14.02	2.26
58	6 Jul 83	2300	9.53	204	9.01	2.60
59	7 Jul 83	0200	10.60	241	10.02	2.14
60	8 Aug 83	0500	16.95	197	16.02	1.59
61	8 Aug 83	1700	11.67	221	11.03	3.99
62	8 Aug 83	2300	12.71	217	12.01	4.07
63	13 Sep 83	0000	10.60	197	11.02	1.59
64	13 Sep 83	0600	13.78	205	14.33	2.88
65	13 Sep 83	1200	11.67	194	12.13	1.36
66	29 Sep 83	2100	21.20	201	22.04	2.26
67	30 Sep 83	0300	15.91	214	16.54	4.05
68	30 Sep 83	0600	12.71	204	13.21	2.60
69	30 Sep 83	0900	14.84	219	15.43	3.91
70	1 Oct 83	2100	11.99	195	13.03	1.62
71	10 Oct 83	1100	17.00	207	18.48	3.21
72	10 Oct 83	2300	11.01	212	11.97	4.0
73	11 Oct 83	1400	11.99	201	13.04	2.26
74	26 Mar 84	1800	11.01	212	11.97	4.00
75	27 Mar 84	0000	11.01	205	11.97	2.88
76	4 Apr 84	2100	10.00	203	10.40	2.29
77	6 Apr 84	0300	8.99	225	9.35	3.73
78	24 Aug 84	2200	10.00	227	10.40	3.79
79	25 Aug 84	0100	15.99	212	15.11	4.0

Numerical Results for Selected 79 Cases

Data Set	JONSWAP Hs (ft)	JONSWAP Tp (s)	NARFET Hs (ft)	NARFET Tp (s)	STWAVE Hs (ft)	STWAVE Tp (s)	BUOY w/swell removed Hs (ft)	BUOY w/swell removed Tp (s)
1	.65	1.89	1.08	2.18	.79	1.8	.79	2.4
2	.66	1.83	1.15	2.23	.89	1.9	.84	2.16
3	.35	1.37	.85	1.96	.62	1.6	.60	2.10
4	.69	1.67	1.35	2.39	1.21	2.1	1.08	2.7
5	.86	1.80	1.54	2.54	1.44	2.3	1.22	2.8
6	1.37	2.22	1.91	2.8	1.80	2.5	1.93	2.7
7	.75	1.82	1.31	2.37	1.12	2.0	1.04	2.7
8	.52	1.52	1.14	2.23	.98	1.9	1.13	2.4
9	1.11	2.17	1.56	2.56	1.35	2.2	1.10	2.7
10	1.07	1.99	1.67	2.63	1.57	2.4	1.60	2.8
11	.81	2.11	1.17	2.25	.85	1.8	.76	2.1
12	.79	2.07	1.16	2.24	.85	1.8	.85	2.4
13	.46	1.50	1.03	2.13	.79	1.8	.68	2.4
14	.89	1.87	1.5	2.51	1.35	2.2	1.20	2.8
15	.65	1.88	1.08	2.17	.79	1.8	.78	2.4
16	1.49	2.28	1.98	2.83	1.87	2.6	2.22	3.4
17	1.04	2.02	1.62	2.6	1.48	2.3	1.33	3.0
18	.48	1.61	.98	2.08	.72	1.7	.74	2.2
19	1.09	2.00	1.7	2.65	1.61	2.4	1.53	3.0
20	1.23	2.08	1.82	2.73	1.74	2.5	1.82	2.8
21	1.26	2.16	1.79	2.71	1.71	2.5	1.70	3.2
22	1.29	2.24	1.76	2.69	1.61	2.5	1.72	3.0
23	.72	2.00	1.09	2.19	.79	1.8	.78	2.2
24	.92	2.19	1.26	2.33	.98	1.9	.63	2.3
25	.81	2.10	1.19	2.26	.89	1.8	.77	2.4
26	.51	1.60	.99	2.09	.82	1.8	.76	2.3
27	.52	1.56	1.11	2.2	.89	1.9	.87	2.4
28	.95	1.91	1.59	2.58	1.48	2.3	1.34	3.0
29	.37	1.36	.94	2.4	.72	1.7	.61	2.2
30	.69	1.81	1.21	2.28	.98	1.9	.72	2.5
31	.33	1.33	.84	1.95	.59	1.7	.47	2.0
32	1.42	2.45	1.73	2.68	1.54	2.3	1.44	2.4
33	1.28	2.28	1.71	2.66	1.44	2.3	1.27	3.0
34	1.02	2.26	1.35	2.4	.92	2.0	.99	2.2
35	.49	1.49	1.11	2.2	.92	1.9	.56	2.4
36	.40	1.35	1.05	2.14	.82	1.8	.63	2.4
37	.48	1.58	.97	2.07	.75	1.8	.87	2.3
38	.30	1.34	.77	1.87	.59	1.6	---	2.0
39	.33	1.34	.83	1.93	.59	1.8	.4	2.17
40	.64	1.77	1.17	2.25	.92	1.9	.91	2.3
41	.90	1.93	1.47	2.49	1.28	2.2	1.30	2.8
42	.51	1.64	1.01	2.11	.75	1.8	.65	2.1
43	.43	1.47	.98	2.08	.75	1.8	.54	2.2
44	.71	1.78	1.28	2.34	1.04	2.0	.76	2.5
45	.49	1.49	1.1	2.19	.92	1.9	.82	2.3

Data Set	JONSWAP		NA FET		STWAVE		BUOY w/swell removed	
	Hs (ft)	Tp (s)	Hs (ft)	Tp (s)	Hs (ft)	Tp (s)	Hs (ft)	Tp (s)
46	.65	1.69	1.25	2.32	1.08	2.0	.91	2.7
47	.81	1.77	1.5	2.51	1.38	2.3	1.28	2.8
48	.35	1.33	.9	2.0	.69	1.7	.55	2.2
49	.65	1.85	1.11	2.2	.82	1.8	.65	2.4
50	.48	1.52	1.06	2.16	.82	1.8	.69	2.3
51	.85	2.13	1.21	2.28	.92	1.9	.80	2.4
52	.40	1.39	.97	2.07	.75	1.8	.62	2.3
53	.49	1.74	.89	2.0	.59	1.7	.58	2.1
54	.31	1.28	.83	1.93	.62	1.7	.47	2.1
55	.61	1.91	.98	2.08	.69	1.7	.38	2.1
56	.37	1.44	.82	1.92	.62	1.7	.57	2.1
57	.69	1.81	1.2	2.28	.98	1.9	.63	2.5
58	.43	1.58	.88	1.99	.59	1.7	.37	2.1
59	.44	1.55	.91	2.02	.69	1.7	.65	2.2
60	.68	1.70	1.29	2.35	1.12	2.0	1.01	2.3
61	.68	1.98	1.05	2.15	.75	1.7	.43	2.2
62	.76	2.06	1.12	2.21	.82	1.8	.69	2.4
63	.43	1.46	.99	2.09	.75	1.8	.74	2.2
64	.79	1.98	1.25	2.32	1.02	1.9	.74	2.4
65	.44	1.44	1.04	2.14	.82	1.8	.80	2.4
66	1.19	2.18	1.69	2.64	1.48	2.3	1.20	2.8
67	1.12	2.35	1.43	2.46	1.12	2.0	1.28	2.4
68	.68	1.85	1.18	2.26	.92	1.9	.76	2.4
69	1.01	2.26	1.36	2.4	.92	2.0	1.25	2.4
70	.53	1.57	1.1	2.19	.92	1.9	.83	2.3
71	1.15	2.28	1.52	2.52	1.25	2.2	1.22	2.8
72	.75	2.05	1.12	2.2	.82	1.8	.67	2.3
73	.63	1.76	1.14	2.23	.89	1.9	.83	2.2
74	.75	2.05	1.12	2.2	.82	1.8	.68	2.4
75	.64	1.84	1.09	2.18	.82	1.8	.79	2.4
76	.48	1.61	.98	2.08	.69	1.7	.60	2.2
77	.53	1.81	.93	2.04	.62	1.7	.70	2.2
78	.55	1.83	.93	2.03	.69	1.7	.53	2.1
79	1.00	2.25	1.32	2.37	.92	2.0	.83	2.5

Sample Output Results from STWAVE

Sample output plots from STWAVE are shown in Figures A1 through A4. These are presented here as a means to verify that the correct grid was input into STWAVE. The wind measurements were taken on Puffin Island at grid points 58,14. The wave buoy was at grid points 64,18.

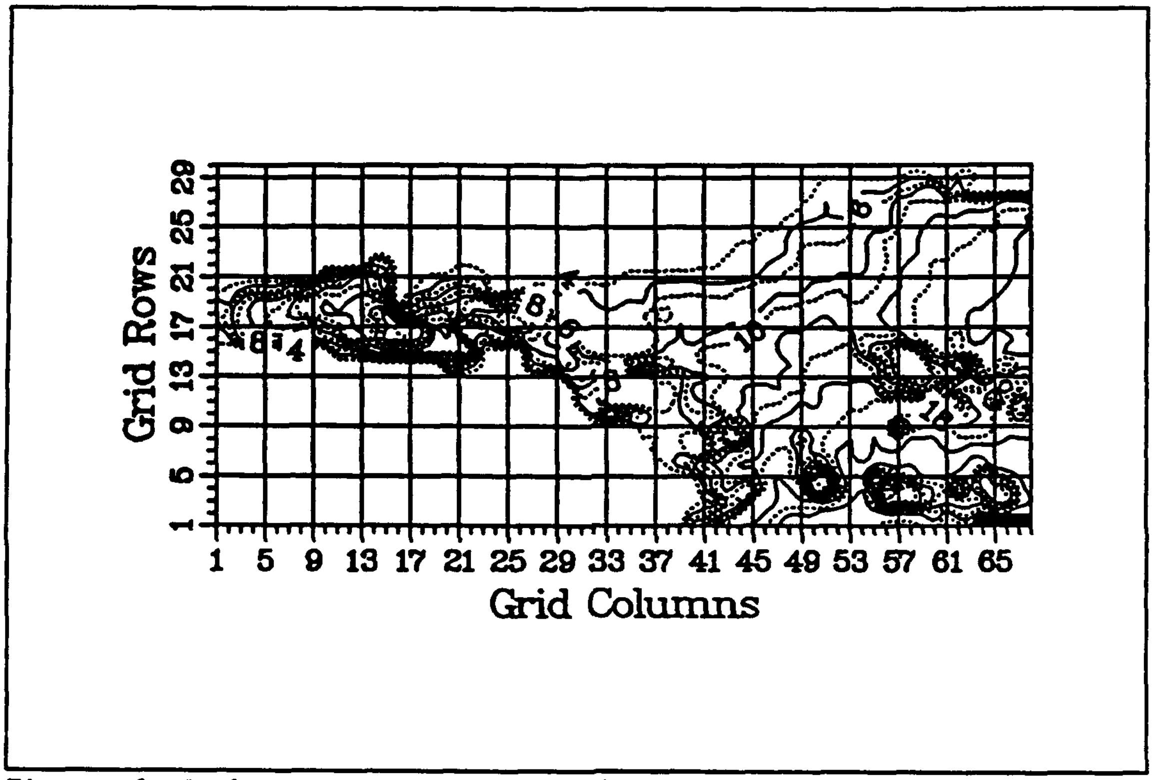

Figure A1 Bathymetry Contours, Kodiak Alaska

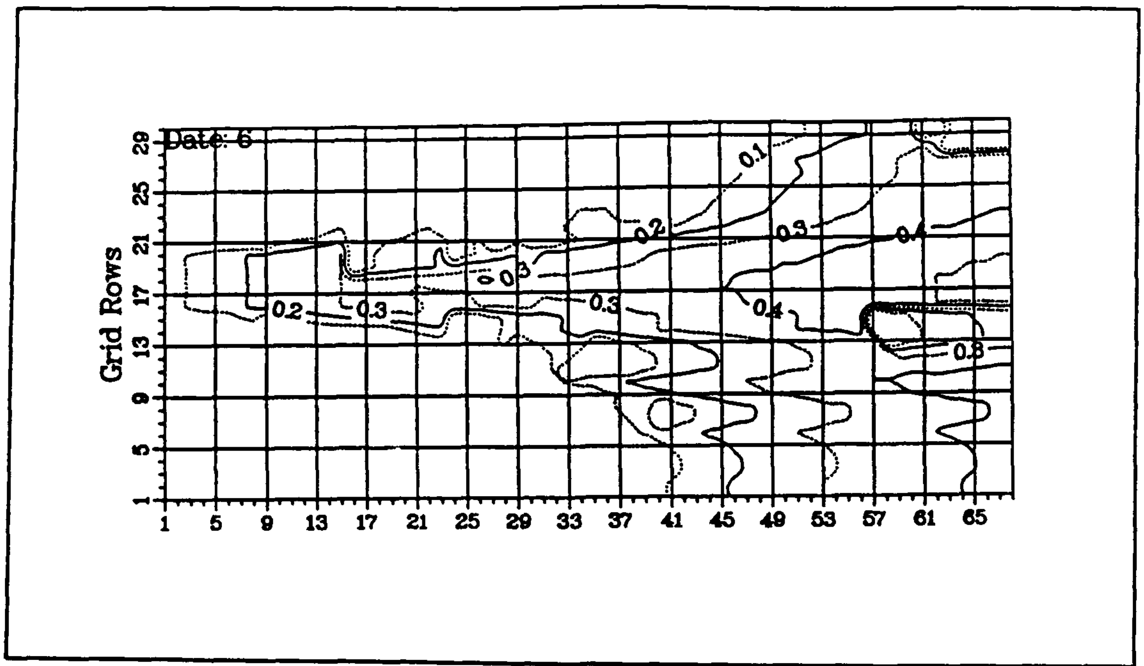

Figure A2 Wave Height Contours, Kodiak Alaska

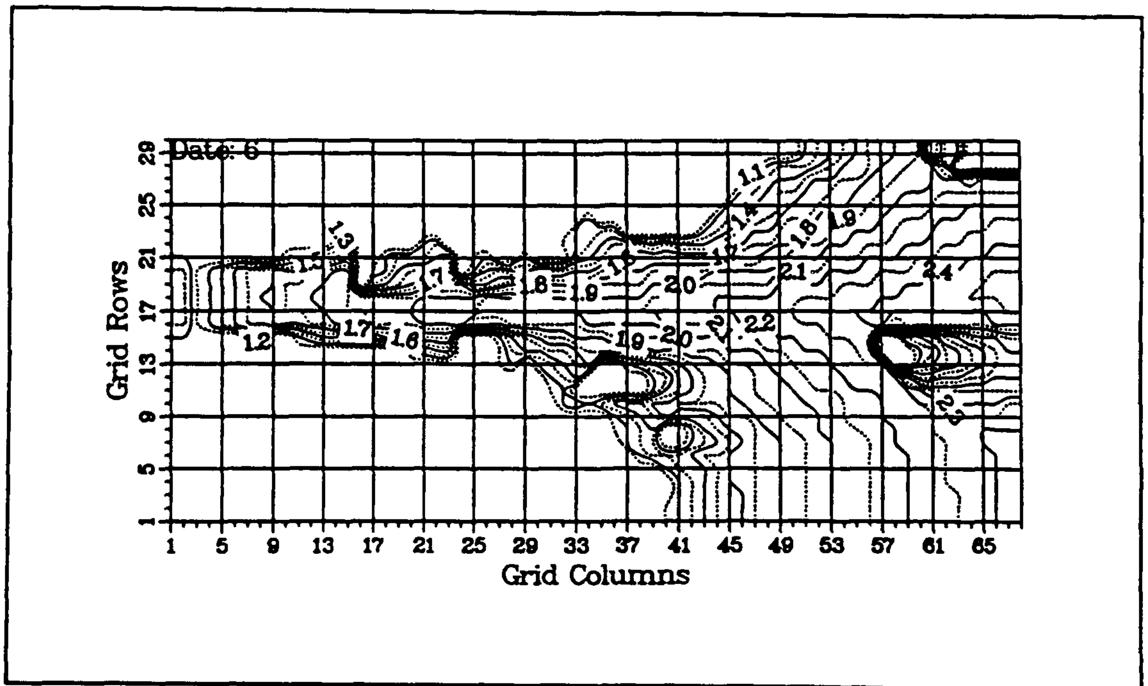

Figure A3 Wave Period Contours, Kodiak Alaska

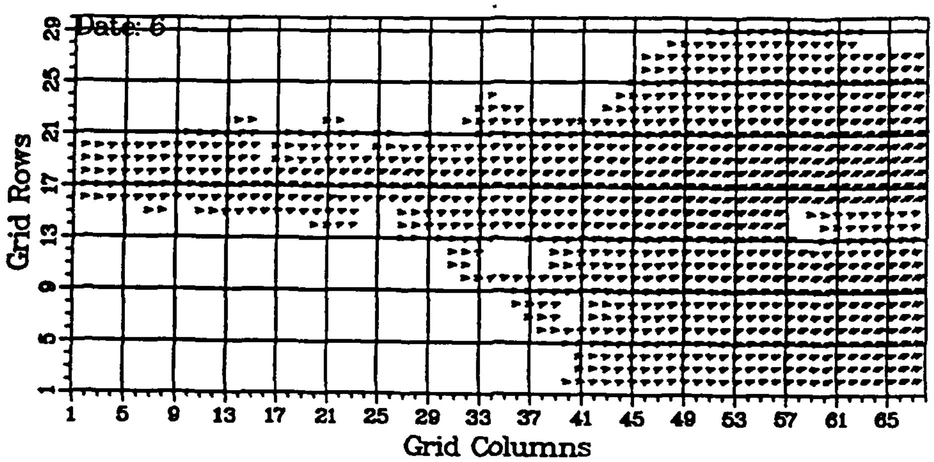

Figure A4 Wave Direction Vectors, Kodiak Alaska

APPENDIX B: FETCH DETERMINATIONS

Fetch Determinations

Figure B1 gives fetch length versus radial direction. Fetch length is the arithmetic average of nine radials spaced at three degree increments centered on the given radial. Results were computed by a computer program in Basic.

Figure B2 shows the Basic program code used to compute fetch length of any desired direction.

Figures B3 through B5 depict the straight line fetches between the buoy and land. The first number appearing on the fetch line radial is the direction in degrees relative to true north, and the second number is the fetch length in inches. The conversion factor that applies to these NOAA charts is 1 inch equals .3157 miles.

FETCH LENGTHS BASED ON 9 RADIALS AT 3 DEGREE INCREMENTS
FOR KODIAK ALASKA

MAIN RADIAL (DEGREE)	FETCH LENGTH (MILES)
194	1.36
195	1.62
196	1.64
197	1.59
198	1.92
199	1.94
200	1.89
201	2.26
202	2.34
203	2.29
204	2.60
205	2.88
206	2.87
207	3.21
208	3.50
209	3.49
210	3.83
211	4.03
212	4.00
213	3.97
214	4.05
215	4.02
216	4.00
217	4.07
218	4.04
219	3.91
220	3.97
221	3.99
222	3.87
223	3.92
224	3.93
225	3.73
226	3.78
227	3.79
228	3.54
229	3.54
230	3.54
231	3.35
232	3.14
233	3.10
234	2.87
235	2.67
236	2.63
237	2.40
238	2.28
239	2.25
240	2.15
241	2.14
242	2.11
243	2.01
244	2.00
245	1.97
246	1.95
247	1.94
248	1.92
249	1.90
250	1.89
251	1.87
252	1.85
253	1.83
254	1.81
255	1.80
256	1.78
257	1.77
258	1.74

Figure B1 Fetch Length vs Direction

```
LPRINT "  FETCH LENGTHS BASED ON 9 RADIALS AT 3 DEGREE INCREMENTS"
LPRINT "                    FOR KODIAK ALASKA"
LPRINT
LPRINT "  MAIN RADIAL (DEGREE)      FETCH LENGTH (MILES)
LPRINT "  --------------------      --------------------"
LPRINT

DIM D(300)
D(180)=1.8:D(181)=1.9:D(182)=1.9:D(183)=2.0:D(184)=2.0:D(185)=2.0:D(186)=2.0
D(187)=2.0:D(188)=2.1:D(189)=2.1:D(190)=2.1:D(191)=2.1:D(192)=2.1:D(193)=2.1
D(194)=2.1:D(195)=2.1:D(196)=2.1:D(197)=2.1:D(198)=9.0:D(199)=9.1:D(200)=9.2
D(201)=9.2:D(202)=9.2:D(203)=9.2:D(204)=9.6:D(205)=9.9:D(206)=8.1:D(207)=8.1
D(208)=8.30:D(209)=8.40:D(210)=10.4:D(211)=10.5:D(212)=10.6:D(213)=11.9
D(214)=13.3:D(215)=13.4:D(216)=11.6:D(217)=17.7:D(218)=18.7:D(219)=19.7
D(220)=19.7:D(221)=19.7:D(222)=19.6:D(223)=17.2:D(224)=16.8:D(225)=13.2
D(226)=9.8:D(227)=9.8:D(228)=9.8:D(229)=9.7:D(230)=9.6:D(231)=7.3
D(232)=7.1:D(233)=6.8:D(234)=6.7:D(235)=6.7:D(236)=6.7:D(237)=6.5
D(238)=6.6:D(239)=6.5:D(240)=6.4:D(241)=6.4:D(242)=6.2:D(243)=6.2
D(244)=6.2:D(245)=6.2:D(246)=6.2:D(247)=6.3:D(248)=6.3:D(249)=6.2
D(250)=6.2:D(251)=6.1:D(252)=6.0:D(253)=5.9:D(254)=5.8:D(255)=5.7
D(256)=5.7:D(257)=5.6:D(258)=5.6:D(259)=5.4:D(260)=5.4:D(261)=5.3
D(262)=5.2:D(263)=5.1:D(264)=5.1:D(265)=5.0:D(266)=5.0:D(267)=4.9
D(268)=4.9:D(269)=4.9:D(270)=4.7

        FOR I = 194 TO 258
        X = D(I-12)+D(I-9)+D(I-6)+D(I-3)+D(I)+D(I+3)+D(I+6)+D(I+9)+D(I+12)
        Y = X/9
        Z = Y * 0.3157
        LPRINT USING "##############                 #.##":I,Z
        NEXT I
```

Figure B2 Basic Program to Compute Fetch Lengths

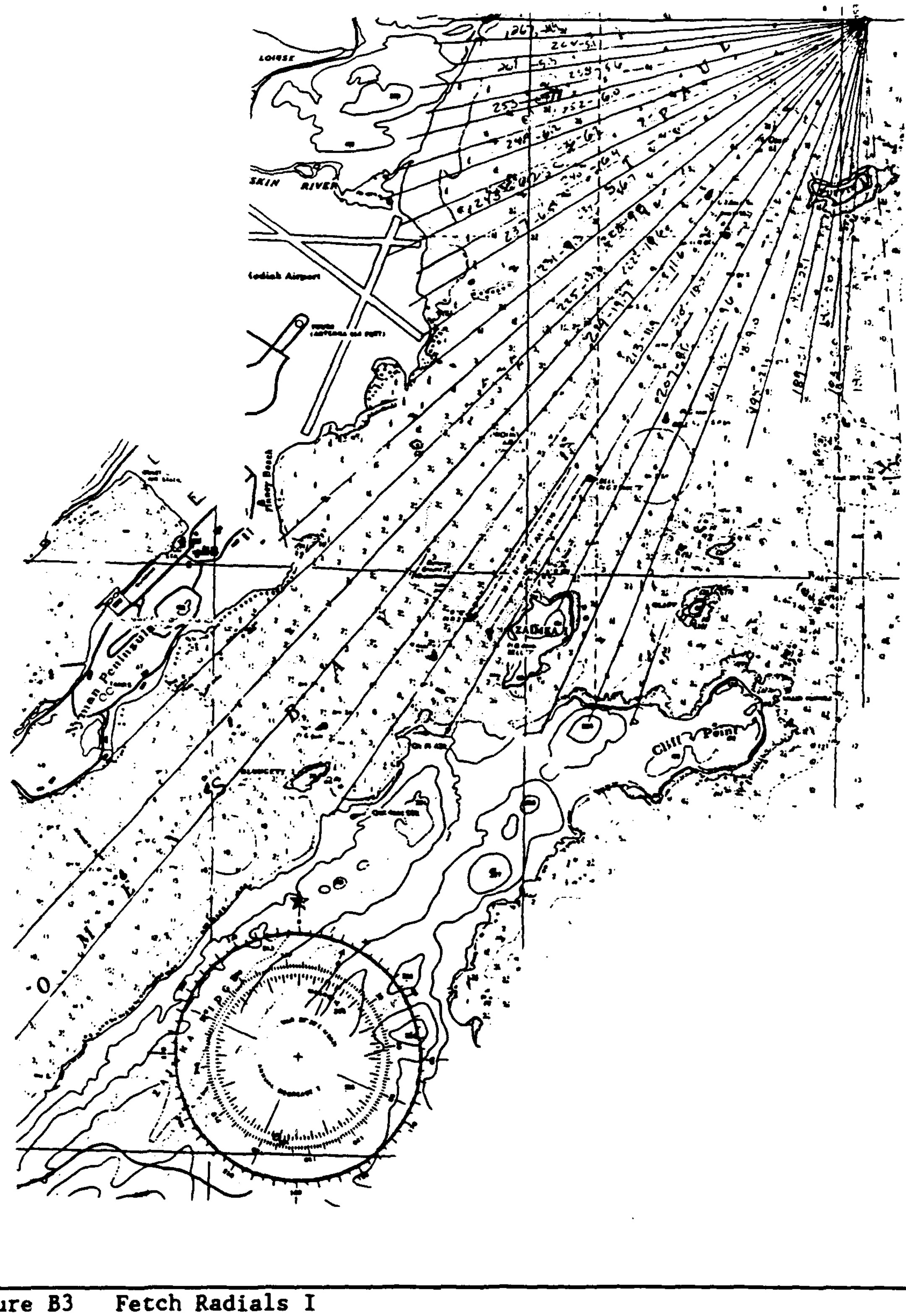

Figure B3 Fetch Radials I

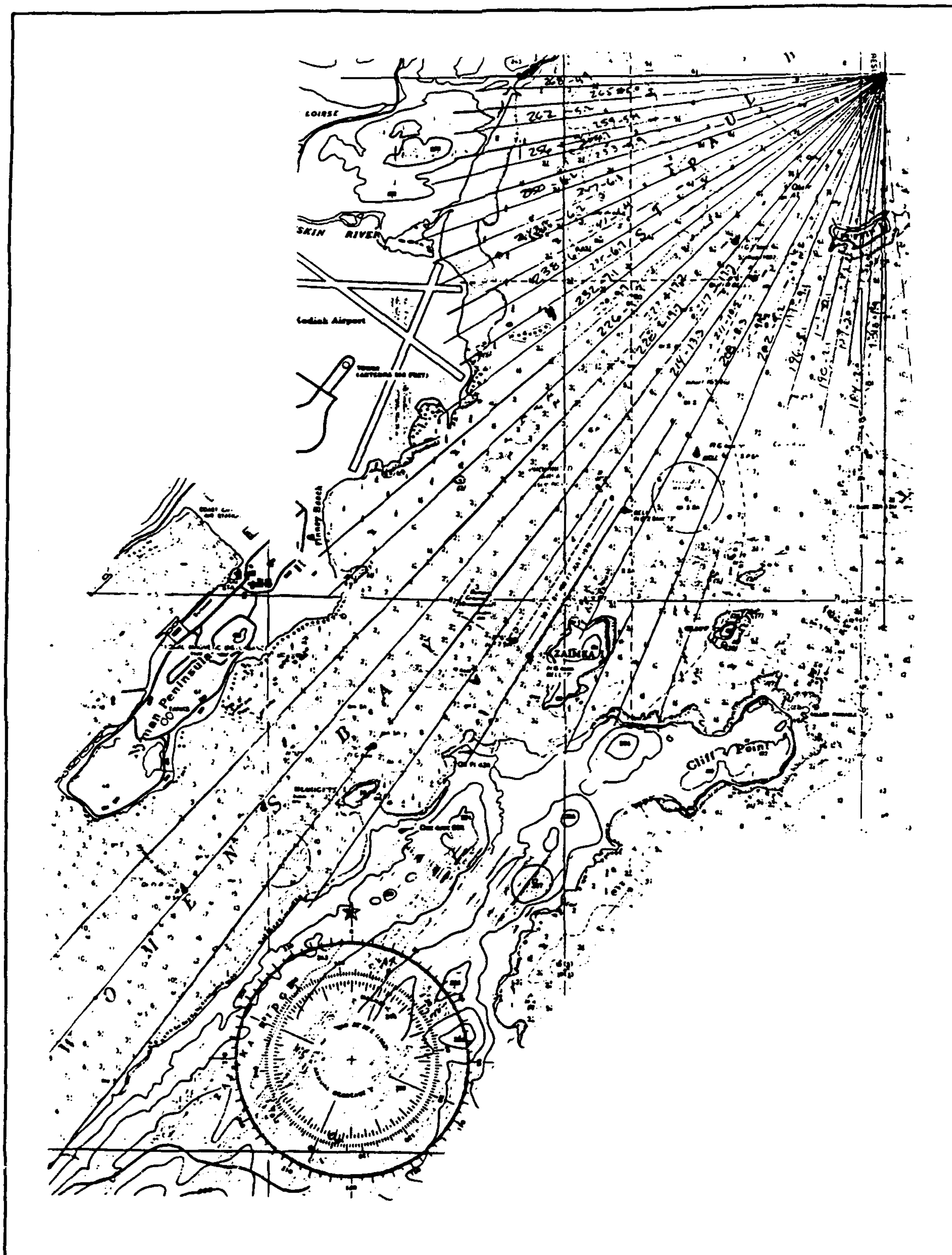

Figure B4 Fetch Radials II

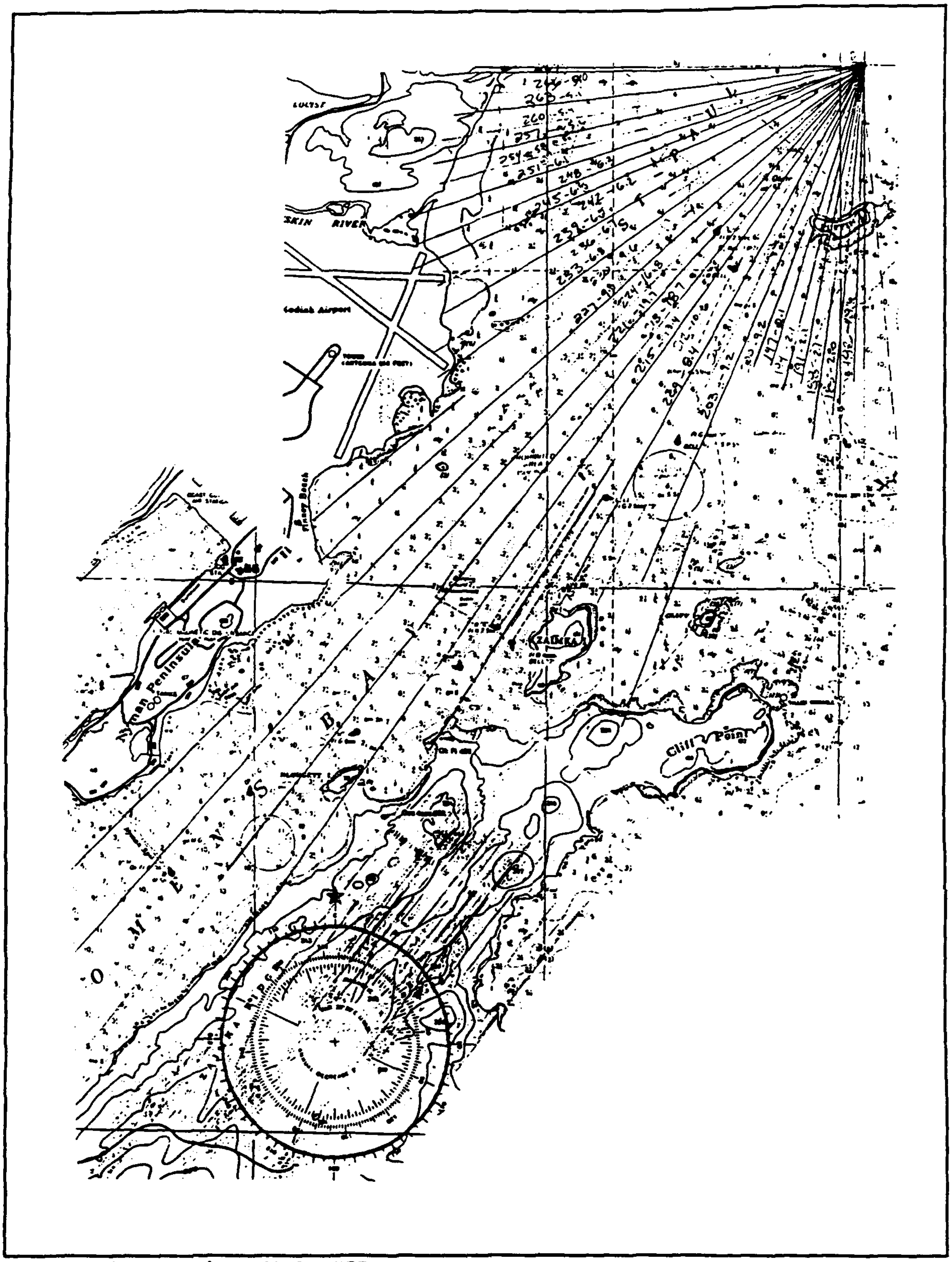

Figure B5   Fetch Radials III

Waterways Experiment Station Cataloging-in-Publication Data

Eisses, Kenneth J.

Evaluation of methods for estimating wind wave growth on narrow irregular fetches / by Kenneth J. Eisses ; prepared for Department of the Army, U.S. Army Corps of Engineers ; monitored by Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station.

58 p. : ill. ; 28 cm. — (Technical report ; CERC-92-8)

Includes bibliographic references.

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